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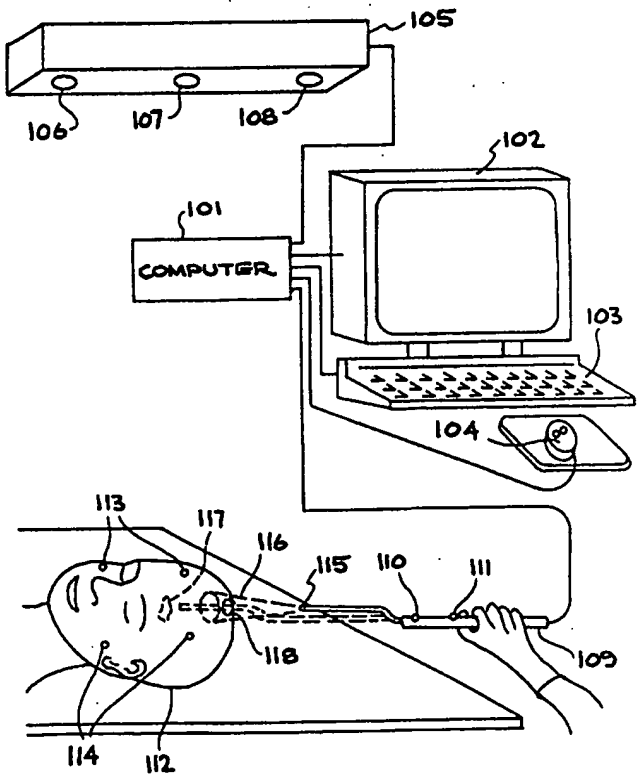
(54) Title: METHOD AND APPARATUS FOR VOLUMETRIC IMAGE NAVIGATION

(57) Abstract

A surgical navigation system has a computer (101) with a memory (202) and a display (102) connected to a surgical instrument or pointer (109) and a position tracking system (105, 110, 111), so that the location and orientation of the pointer (109) are tracked in real time, and conveyed to the computer (101). The computer memory (202) is loaded with data from an MRI, CT, or other volumetric scan of a patient, and this data is utilized to dynamically display 3-dimensional perspective images in real time of the patient's anatomy from the viewpoint of the pointer (109).



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Description

Method and Apparatus for Volumetric Image Navigation

Technical Field

This invention pertains generally to systems and methods for generating images of three dimensional objects for navigation purposes, and more particularly to systems and methods for generating such images in medical and surgical applications.

Background Art

Precise imaging of portions of the anatomy is an increasingly important technique in the medical and surgical fields. In order to lessen the trauma to a patient caused by invasive surgery, techniques have been developed for performing surgical procedures within the body through small incisions with minimal invasion. These procedures generally require the surgeon to operate on portions of the anatomy that are not directly visible, or can be seen only with difficulty. Furthermore, some parts of the body contain extremely complex or small structures and it is necessary to enhance the visibility of these structures to enable the surgeon to perform more delicate procedures. In addition, planning such procedures requires the evaluation of the location and orientation of these structures within the body in order to determine the optimal surgical trajectory.

New diagnostic techniques have been developed in recent years to obtain images of internal anatomical structures. These techniques offer great advantages in comparison with the traditional X-ray methods. Newer techniques include microimpulse radar (MIR), computer tomography (CT) scans, magnetic resonance imaging (MRI), positron emission tomography (PET), ultrasound (US) scans, and a variety of other techniques. Each of these methods has advantages and

drawbacks in comparison with other techniques. For example, the MRI technique is useful for generating three-dimensional images, but it is only practical for certain types of tissue, while CT scans are useful for generating images of other anatomical structures. Ultrasound scanning, in contrast, is a relatively rapid procedure; however it is limited in its accuracy and signal-to-noise ratio.

The imaging problem is especially acute in the field of neurosurgery, which involves performing delicate surgical procedures inside the skull of the patient. The above techniques have improved the surgeon's ability to locate precisely various anatomical features from images of structures within the skull. However this has only limited usefulness in the operating room setting, since it is necessary to match what the surgeon sees on the 2D image with the actual 3D patient on the operating table. The neurosurgeon is still compelled to rely to a considerable extent on his or her knowledge of human anatomy.

The stereotactic technique was developed many years ago to address this problem. In stereotactic surgery, a frame of reference is attached to the patient's head which provides reference points for the diagnostic images. The device further includes guides for channeling the surgical tool along a desired trajectory to the target lesion within the brain. This method is cumbersome and has the drawback that the surgeon cannot actually see the structures through which the trajectory is passing. There is always the risk of damage to obstacles in the path of the incision, such as portions of the vascular or ventricular system. In essence, with previous neurosurgical techniques the surgeon is in the position much like that of a captain piloting a vessel traveling in heavy fog through waters that have many hazards, such as shoals, reefs, outcroppings of rocks, icebergs, etc. Even though the captain may have a very good map of these hazards, nevertheless there is the constant

problem of keeping track of the precise location of the vessel on the map. In the same way, the neurosurgeon having an accurate image scan showing the structures within the brain must still be able to precisely locate where the actual surgical trajectory lies on the image in order to navigate successfully to the target location. In the operating room setting, it is further necessary that this correlation can be carried out without interfering with the numerous other activities that must be performed by the surgeon.

The navigation problem has been addressed in United States Patent No. 5,383,454, issued January 24, 1995 (Bucholz). This patent describes a system for indicating the position of a surgical probe within a head on an image of the head. The system utilizes a stereotactic frame to provide reference points, and to provide means for measuring the position of the probe tip relative to these reference points. This information is converted into an image by means of a computer.

United States Patent No. 5,230,623, issued July 27, 1993 (Guthrie), discloses an operating pointer whose position can be detected and read out on a computer and associated graphics display. The pointer can also be used as a "3D mouse" to enable the surgeon to control the operation of the computer without releasing the pointer.

United States Patent No. 5,617,857, issued April 8, 1997 (Chader et al.) sets forth an imaging system and method for interactively tracking the position of a medical instrument by means of a position-detecting system. The pointer includes small light-emitting diodes (LED), and a stationary array of radiation sensors is provided for detecting pulses emitted by these LED's and utilizing this information to ascertain dynamically the position of the pointer. Reference is made also to United States Patent No. 5,622,170, issued April 22, 1997 (Schulz), which describes a

similar system connected to a computer display for displaying the position of an invasive surgical probe relative to a model image of the object being probed (such as a brain).

United States Patent No. 5,531,227, issued July 2, 1996 (Schneider) explicitly addresses the problem recognized in many other references that it is desirable to provide a real time display of a surgical probe as it navigates through the brain. This patent describes a system for providing images along the line of sight of the surgeon in a dynamic real-time fashion. In this system the images that are displayed are resliced images from a three-dimensional data reconstruction which are sections or slices orthogonal to the line of sight, taken at various positions along this line specified by the user. Thus, while the viewpoint for the line of sight is always external to the body, the sectional planes that are used to define the virtual images may constitute various slices through the body chosen by the surgeon. These images may be superimposed on actual images obtained by an image recording device directed along the line of sight such as a video camera attached to the surgeon's head, and the composite images may be displayed.

The systems described above attempt to address the navigation problem in various ways, and they all have the common drawback of requiring a certain level of abstract visualization by the surgeon during an operating room procedure. When the surgeon is proceeding through the brain toward a target tumor or lesion, it is desirable to be fully aware of all of the structures around the surgical trajectory. With previous systems the displays that are presented do not provide all of this information in a single convenient real-time display, and they require the viewer to piece together and re-orient the displayed information to obtain a mental picture of the surrounding structures. These are serious practical disadvantages in an operating

room setting. What is absent from previous systems is a 3D display that shows, in a real-time view, the various structures looking ahead from the surgical probe along a line of sight into the brain in three and two dimensions, including structures hidden by other features.

Disclosure of Invention

The present invention provides an improved system and method for displaying 3D images of anatomical structures in real time during surgery to enable the surgeon to navigate through these structures during the performance of surgical procedures. This system is also useful in planning of surgical procedures. The system includes a computer with a display and input devices such as a keyboard and mouse. The system also includes a position tracking system that is connected both to the computer and also to the surgical probes or other instruments that are used by the surgeon. The position tracking system provides continual real time data to the computer indicating the location and orientation of the surgical instrument in use. The computer further includes a memory containing patient data produced by imaging scans, such as CT or MRI scans, from which 2-dimensional and 3-dimensional images of the anatomical structure may be generated. Means are provided for registration of these images with respect to the patient.

The computer memory is further provided with programs that control the generation of these anatomical images. These programs include software for segmentation of the scan images to identify various types of structures and tissues, as well as the reconstruction of 2D and 3D images from the scan data. This software allows these images to be displayed with various magnifications and orientations, and with various sectional views produced by slice planes in various locations and orientations, all controlled by the surgeon.

This image-generating software has the important feature that it produces 3D images that are perspective views of the anatomical structures, with user-controlled means for varying the viewing orientation and location, and also varying the displayed transparency or opacity of various types of tissues, structures, and surfaces in the viewed region of interest. This enables the user to effectively "see through" surfaces and structures in the line of sight of the image to reveal other structures that would otherwise be hidden in that particular view.

Further, the images are generated from the viewpoint of the surgical probe or instrument that is in use, looking from the tip of the instrument along its longitudinal axis. Thus, when an invasive surgical instrument such as a scalpel or forceps is inserted into an incision in the body, the display provides a three dimensional perspective view of anatomical structures from a viewpoint inside the body. These images are all generated in real time "on the fly". Thus, as the instrument is moved or rotated, the position tracking system continually provides data to the computer indicating the location and orientation of the instrument, and the displayed image is continually updated to show the structures toward which the instrument is pointing.

In addition, for probes or instruments being used that are capable themselves of generating images, such as ultrasound probes, endoscopes, or surgical microscopes, the system provides means for integrating these images with those generated from the scan data. The software enables the user to overlay the "actual images" generated by these instruments with the "virtual images" generated from the scan data.

It is an object of this invention to provide a system and method for generating an image in three dimensional perspective of anatomical structures encountered by a surgeon during the performance of surgical procedures.

A second object of this invention is to provide a system and method for generating such an image with user-controlled means for varying the location and orientation of the viewpoint corresponding to the image.

Another object of this invention is to provide a system and method for generating such an image with user-controlled means for varying the opacity of structures and surfaces in the viewed region of interest, so that the displayed image shows structures and features that would be otherwise hidden in a normal view.

Yet another object of this invention is to provide a system and method for generating such an image with a viewpoint located at the tip of the instrument being used by the surgeon in the direction along the longitudinal axis of the instrument.

Still another object of this invention is to provide a system and method for generating such an image in real time, such that the displayed image continually corresponds to the position of the instrument being used by the surgeon.

Yet a further object of this invention is to provide a system and method for comparing and combining such an image with the image produced by an image-generating instrument being used by the surgeon.

These and other objects, advantages, characteristics and features of the invention may be better understood by examining the following drawings together with the detailed description of the preferred embodiments.

Brief Description of Drawings

Figure 1 is a schematic perspective drawing of the apparatus of the present invention in operating room use during the performance of neurosurgical procedures.

Figure 2 is a schematic block diagram of the computer system and optical tracking system of the present invention.

Figure 3 is a schematic block diagram of the navigation

protocol using pre-operative data that is followed in carrying out the method of the present invention.

Figure 4 is a schematic block diagram of the navigation protocol using ultrasound intra-operative data that is followed in carrying out the method of the present invention.

Figure 5 is a schematic block diagram of the endoscopic protocol that is followed in carrying out the method of the present invention.

Figure 6 is a schematic flow chart of the pre-operative computer program that implements the pre-operative protocol of the present invention.

Figure 7 is a schematic flow chart of the intra-operative ultrasound computer program that implements the ultrasound protocol of the present invention.

Figure 8 is a schematic flow chart of the intra-operative endoscope computer program that implements the endoscope protocol of the present invention.

Figure 9 is a drawing of a display generated according to the present invention, showing axial, coronal, and sagittal views of a head, together with a three-dimensional perspective view of the head taken from an exterior viewpoint.

Figure 10 is a drawing of a display generated according to the present invention, showing sectional axial, coronal, and sagittal views of a head, together with a three-dimensional perspective view of the head taken from an interior viewpoint.

Figure 11a is a drawing of a plastic model of a human skull and a surgical probe that has been used to demonstrate the present invention.

Figure 11b is another drawing of the model skull of Figure 11a, with the top of the skull removed to show model internal structures for demonstration purposes.

Figure 12 is a simplified reproduction of two displays

produced by the present invention for the model skull shown in Figures 11a, 11b.

Figure 13 is a simplified reproduction of two further displays of the invention for the skull in Figures 11a, 11b.

Figure 14 is a reproduction of a composite display produced by the present invention for an actual human head.

Best Mode for Carrying Out the Invention

Figure 1 shows the apparatus of the invention as used in performing or planning a neurosurgery operation. In this drawing the patient's head (112), has a tumor or lesion (117), which is the target object of the operation. Fiducial markers (113), (114) are attached to the head to enable registration of images generated by previously obtained scan data according to techniques familiar to persons of ordinary skill in the relevant art. A surgical probe or instrument (109) held by the surgeon is directed toward the tissues of interest. A computer (101) is connected to user input devices including a keyboard (103) and mouse (104), and a video display device (102) which is preferably a color monitor. The display device (102) is located such that it can be easily viewed by the surgeon during an operation, and the user input devices (103) and (104) are placed within easy reach to facilitate use during the surgery. The apparatus further includes a position tracking system, which is preferably an optical tracking system (hereafter "OTS") having a sensing unit (105) mounted overhead in view of the operating table scene, and at least two light emitting diodes (LED's) (110), (111) mounted on the surgical instrument (109). These LED's preferably emit continuous streams of pulsed infrared signals which are sensed by a plurality of infrared detectors (106), (107), (108) mounted in the sensing unit (105) in view of the surgical instrument (109). The instrument (109) and the sensing unit (105) are both connected to the computer (101),

which controls the timing and synchronization of the pulse emissions by the LED's and the recording and processing of the infrared signals received by the detectors (106) - (108). The OTS further includes software for processing these signals to generate data indicating the location and orientation of the instrument (109). The OTS generates the position detecting data on a real time continuous basis, so that as the surgical instrument (109) is moved, its position and orientation are continually tracked and recorded by the sensing unit (105) in the computer (101). The OTS may be preferably of the type known as the "FlashPoint 3-D Optical Localizer", which is commercially available from Image Guided Technologies of Boulder, Colorado, similar to the systems described in U.S. Patent Nos. 5,617,857 (Chader, et al.) and 5,622,170 (Schulz) discussed previously. However the invention is not limited to this particular OTS, and other position tracking systems, such as sonic position detecting systems, may also be utilized.

As illustrated in Figure 1, the surgical instrument (109) is elongated in shape, having a longitudinal axis and tip (115) pointing toward the tissues of interest. The instrument may be an endoscope having a conical field of view (116) that is indicated by dotted lines in Figure 1. The instrument shown in the Figure is held at a position external to the patient's head. If an incision (118) has been made into the skull, the instrument may be inserted through the incision; this alternative position is shown by dotted lines in Figure 1. In both positions the instrument is held so that there is an unobstructed line of sight between the LED's (110), (111) and the sensing unit (105). In endoscopic and other optical viewing applications, the instrument may include a laser targeting system (not shown in the drawings) to illuminate and highlight the region under examination.

Figure 2 shows a schematic block diagram of the

computer system connected to the position tracking system. The computer (101) includes a central processing unit (CPU) (201) communicative with a memory (202), the video display (102), keyboard and mouse (103), (104), optical detectors (106) - (108), and the LED's mounted on the surgical instrument (109). The computer memory contains software means for operating and controlling the position tracking system. In an alternative preferred embodiment, the OTS components (105) - (109) may be connected to and controlled by a separate computer or controller which is connected to the computer (101) and provides continual data indicating the position and orientation of the surgical instrument (109).

The above apparatus is operated to carry out surgical protocols that are illustrated schematically in Figures 3 - 5. Figure 3 is a schematic block diagram of the protocol for handling pre-operative data ("pre-op protocol") to generate images during surgery according to the present invention. It is assumed that three-dimensional image data of the patient's head have been previously obtained from one or more of the techniques that are known to persons of ordinary skill in the medical imaging arts. Preferably these data are acquired from CT, MIR and/or MRI scan techniques to provide images with improved accuracy and detail, compared to ultrasound scan data for example. The scan data are loaded and stored (301) into the computer memory (202) through additional input means such as disk drives or tape drives, not shown in the drawings.

The patient data is registered (302) according to one of the generally known techniques. This procedure may be either a three-dimensional registration of the entire data set, or a slice-by-slice sequence of two-dimensional registrations. Following the three-dimensional registration, the image is reconstructed (303) in memory, using volumetric or surface rendering to produce an array of

3-dimensional voxel data. Segmentation (304) is then carried out on these data to distinguish various anatomical features, such as different types of material in the head (bone, brain tissue, vascular and ventricular structures, etc.) and the location of surfaces, using one or more of known segmentation techniques. Preferably the segmentation process includes assigning different display colors to different types of structures to facilitate their identification and distinction in a color video display. For example, the vascular system may be displayed in red, the ventricular system may be shown in blue, bones may be colored brown, and so on. In a preferred embodiment these assignments may be varied by the user by means of the keyboard (103) or mouse (104). Also in a preferred embodiment the display opacities may be varied by the user by means of the keyboard (103), mouse (104), or other input device (such as a voice-activated device) to further facilitate their identification and distinction of hidden or obstructed features in the video display. In an alternative protocol in which 2-dimensional registration is carried out, segmentation (309) can be done for each 2-dimensional image sample, and the 3-dimensional data are then reconstructed (310) from the segmented data slices. This alternative protocol is shown by dotted lines in the Figure.

Referring still to Figure 3, the next phase of the pre-op protocol is to determine the location and orientation of the view vector (305) to define the image to be displayed. This view vector is obtained by querying the OTS to ascertain the current location and orientation of the surgical instrument (109). With this information, the three-dimensional scan data is then manipulated (306) to position and orient the resulting three-dimensional perspective view and to define cutting planes and reference markers in the displayed image indicating and clarifying this view. The manipulated three-dimensional perspective

image is then displayed (307) on the video display (102). In addition, other two-dimensional images, such as 2D sectional views for any cutting planes, are preferably also displayed along with the 3D perspective display for purposes of elucidation.

Finally, the pre-op protocol is a continuing loop process in which the OTS is repeatedly queried (308) for changes in the location of the view vector corresponding to changes in the position and orientation of the surgical instrument (109). Thus the displayed images are continually being updated during the surgical procedure, and the resulting displays are constantly refreshed in real time. The image data are also stored or buffered and made available for further use (311) according to subsequent protocols.

The surgical instrument (109) may include an ultrasound transducer located at the tip (115), which itself scans and detects ultrasound imaging data when placed in contact with the patient's head. Figure 4 is a schematic block diagram showing the intra-operative ("intra-op") ultrasound ("US") protocol for handling the US image data during surgery. Typically the ultrasound transducer is a phased focusing array which generates data from a planar fan-shaped sector of the anatomical region of interest, where the central axis of the transducer lies in the plane of the scan sector which, in this context, is collinear with the longitudinal axis of the surgical instrument (109). By rotating the instrument and transducer about this axis, US scan data is collected and stored (401) for a cone-shaped volume in the region of interest. This cone defines the "field of view" of the transducer scan.

The location and orientation of the transducer is tracked and determined (402) by the OTS, and the US data is used to reconstruct (403) three-dimensional intra-op image data for the region of interest. This data is manipulated

(404) in a way analogous to the manipulation (306) of the pre-op data, and then used to generate three-dimensional images (405), together with any desired corresponding two-dimensional images of the ultrasound data. These intra-op images are fused (406) with the pre-op images generated by the pre-op protocol (311), and the composite images are further displayed. Finally, the OTS is continually strobed (407), and the ultrasound images are constantly refreshed.

Figure 5 is a schematic block diagram of the intra-op protocol in which an endoscope is place at the tip 115 of the surgical instrument (109). This protocol is also applicable for procedures utilizing a surgical microscope in place of the endoscope. Image data is acquired (501), using a CCD camera or other known technique, representing a 2-dimensional image in a plane orthogonal to the line of sight of the endoscope or microscope, which in this context is the longitudinal axis of the surgical instrument (109). The location and orientation of the instrument is tracked and determined (502) by the OTS, and analog-to-digital ("A/D") conversion (503) is carried out on the data. The location of the viewpoint is determined (504) from the OTS data, and the endoscope or microscope image data is manipulated (505) to generate the desired image (506) for display. These intra-op images are fused (508) with the pre-op images generated by the pre-op protocol (311), and the composite images are further displayed. Finally, the OTS is continually strobed (507), and the ultrasound images are constantly refreshed.

The foregoing protocols are implemented by program modules stored in the memory (202) of the computer (101). Figure 6 is a schematic block diagram of a flow chart for a program that implements the pre-op protocol. The program starts (601) by causing the computer to receive and load (602) previously obtained scan data for the patient, such as MRI or CT data. The computer further reads data from the

OTS (603) to register the scanned patient data (604). For 3D volumetric rendering, the scanned data is used to reconstruct image data (605) in three dimensions, and segmentation (606) is carried out on this reconstruction. In an alternative embodiment, shown by dotted lines in the Figure, segmentation is carried out on 2D slices (615), and these segmented slices are then reconstructed into the full 3D image data.

The program next reads input data from the keyboard (103) or mouse (104) to enable the user to select a field of view for image displays (607). The image data is then manipulated and transformed (608) to generate the requested view, along with any selected reference markers, material opacities, colors, and other options presented to the user by the program. In addition, the user may request a 3D display of the entire head, together with a superimposed cone showing the field of view for an endoscope, microscope, ultrasound transducer, or other viewing device being used during the surgery. The resulting manipulated image is then displayed (609) preferably in color on the video display (102). The computer next reads the OTS data (610) and determines (611) whether the surgical instrument has moved. If so, program control returns to the selection of a new field of view (607) and the successive operations (608) - (610) shown in Figure 6. If the position of the instrument has not changed, the displayed image is stored (612), refreshing any previously stored display image. The program further looks for requests from the user (613) whether to discontinue operation, and it there are no such requests, the operations (611) and (612) are repeated. Thus the computer remains in a loop of operations until the user requests termination (614).

Figure 7 is a schematic block diagram of a flow chart for a program that implements the ultrasound intra-op protocol. The program starts (701) by causing the computer

to receive and load the data from a US transducer at the tip (115) of the surgical instrument (109). Such data is produced normally using polar or spherical coordinates to specify locations in the region of interest, and the program converts (703) this data preferably to Cartesian coordinates. Next, OTS data is read (704) to determine the position and orientation of the surgical instrument (109), and US data from the aggregation of aligned data slices is utilized to reconstruct 3D image data (705) representing the US scan data. This image data is manipulated and transformed (706) by the program in a manner similar to the manipulation (608) of the pre-op data (608), and the resulting image is displayed (707).

Similarly to the pre-op program shown in Figure 6, the OTS is queried (709) to determine whether the surgical instrument has moved (713), and if so a new US display image is constructed. In a preferred embodiment, the program queries the user (716) whether to carry out another US scan of the region of interest. If so, program control returns to the operation (702) in Figure 7 and fresh US data is obtained by the US transducer. If another scan is not requested (716), the program returns to operation (705) and a new 3D image is reconstructed from the present US scan data.

If the OTS query (709) determines that the surgical instrument has not moved since the last query, the US image is fused (710) with the pre-op image obtained by the program shown in Figure 6, and the combined image is displayed (711). The OTS is again queried (712) to determine (713) whether the surgical instrument has moved. If so, the program returns to the new scan user query (716). Otherwise the program further looks for requests from the user (714) whether to discontinue operation, and if there are no such requests, the operation (713) is repeated. Thus the computer remains in a loop of operations until the user

requests termination (715), similarly to the pre-op program of Figure 6.

The endoscope/microscope intra-op protocol is implemented preferably by the endoscope intra-op program having a flow chart shown in schematic block diagram form in Figure 8. Upon starting (801), the program causes the computer to receive and load image data from the endoscope (802). This data is digitized (803) and preferably displayed (804) on the video display (102). The OTS is queried (805) to receive information determining the location and orientation of the endoscope (806). Using this information, the pre-op data obtained by the pre-op program illustrated in Figure 6 is retrieved (807), and utilized to reconstruct a 3-dimensional virtual image (808) from the viewpoint of the endoscope. This image is displayed (809), in a manner similar to the 3D display of images by the pre-op program illustrated in Figure 6. This image is fused (810) with the endoscope image displayed in operation (804), and the combined image is also displayed (811). The OTS is then strobed (812) to determine (813) whether the endoscope has moved since the last query, and if so, program control returns to the operation (802) which refreshes the image data received by the endoscope. Otherwise the program further looks for requests from the user (814) whether to discontinue operation, and if there are no such requests, the operation (813) is repeated. Thus the computer remains in a loop of operations until the user requests termination (815), similarly to the pre-op and intra-op programs of Figures 6 and 7.

The foregoing program modules may be designed independently, and they can be configured also to run independently. Thus, the pre-op program may be completed, followed by running of either or both of the intra-op programs. Preferably, however, these programs operate in parallel during surgery so that the pre-op data images and

intra-op data images are all continually refreshed as the operation proceeds. Known methods for parallel execution of programs may be utilized to accomplish this result.

The above programs are carried out preferably on a computer (101) that is adapted for computer graphics applications. Suitable computers for these programs are commercially available from Silicon Graphics, Inc. of Mountain View, California. Graphics software modules for most of the individual image processing operations in the above programs are also available from Silicon Graphics, Inc. as well as other sources.

Referring now to Figure 9, the drawing shows a highly simplified sketch of a three-dimensional image display (901) obtained by the above system with the surgical probe (109) of Figure 1 in the position illustrated, pointing toward the target lesion or tumor (117) inside the patient's head (112). The edge of the display (901) is shown by the border (900). The display (901) is a perspective view from the tip (115) of the probe (109). This display is continuously refreshed, so that as the probe (109) is moved the displayed image (901) immediately changes. It will be noted that, although the probe (109) is shown entirely outside the patient's head, the display (901) shows internal anatomical structures such as the brain and the target lesion (117). With the present system, the display characteristics can be adjusted in real time to emphasize or de-emphasize the internal structures. These structures may be distinguished by displays with different colors for different types of material. Also, the display opacity of the skin, skull, and brain tissue may be reduced to provide or emphasize further structural details regarding the target lesion (117). In short, the display (901) effectively equips the surgeon with "X-ray eyes" to look at hidden structures through obstructing surfaces and objects. With this display, the entire internal structure of the head may be examined and

studied to plan a surgical trajectory before any incision is made. Furthermore, if the surgical instrument (109) is a scalpel, the display (901) allows the surgeon to see any structures immediately behind a surface prior to the first incision. Figure 9 shows also the conventional axial (902), coronal (903) and sagittal (904) 2D displays for purposes of further clarification and elucidation of the region under examination.

When the surgical instrument (109) is an endoscope or US transducer, the field of view (116) is also indicated in the display (901) by the quasi-circular image (905) indicating the intersection of the conical field of view (116) with the surface of the skin viewed by the endoscope (109). This conical field of view is also superimposed, for completeness, in the 2D displays (902) - (904). In a preferred embodiment, displays are also presented showing the actual image seen by the endoscope in the field of view (905), and the 3D perspective image for the same region in the field of view (905); these auxiliary displays are not shown in the drawings. Similar auxiliary displays are preferably included when the instrument (109) is an ultrasound transducer.

After an incision (118) has been made in the patient's head, the endoscope may be inserted to provide an internal view of the target anatomy. Referring now to Figure 10, the drawing shows a highly simplified sketch of a three-dimensional image display (1001) obtained by the above system with the endoscope (109) of Figure 1 in the alternative position shown by the dotted lines, pointing toward the target lesion or tumor (117). The edge of the display (1001) is shown by the border (1000). The display (1001) has been manipulated to provide a three-dimensional sectional view with a cutting plane passing through the tip (115) of the endoscope (109) and orthogonal to its axis. Again, the endoscope field of view (905) is indicated in the

display, and in a preferred embodiment auxiliary displays are also presented showing the actual image seen by the endoscope in the field of view (905), and the 3D perspective image for the same region in the field of view (905); these auxiliary displays are also not shown in Figure 10. This Figure further preferably includes also the conventional axial (1002), coronal (1003) and sagittal (1004) 2D displays for purposes of further clarification and elucidation.

Figures 11a, 11b, 12 and 13 illustrate further the three-dimensional displays that are produced by a preferred embodiment of the present invention. Referring to Figures 11a, 11b, a plastic model of a skull has been fabricated having a base portion (1102) and a removable top portion (1101). These Figures show the model skull (1101), (1102) resting on a stand (1106). Figure 11a also shows a pointer (1104) with LED's (1105) connected to an OTS (not shown in the drawing) that has been used to generate displays according to the invention. A plurality of holes (1103) in the top portion (1101) are provided, which allow the pointer (1104) to be extended into the interior of the skull. Figure 11b shows the skull with the top portion (1103) removed. A plastic model of internal structures (1107) is fabricated inside the skull; these internal structures are easily recognizable geometric solids, as illustrated in the Figure.

The skull of Figures 11a, 11b has been scanned to generate "pre-op" image data, which has been utilized to produce the displays shown in Figures 12, 13. The edges of the displays in Figures 12 and 13 are shown by the borders (1200), (1300) respectively. Figure 12 is a composite of two displays (1201), (1202) of the skull with the pointer (1104) directed toward the skull from a top center external location, similar to the location and orientation of the pointer shown in Figure 1. The display (1201) is a three-dimensional perspective view from this pointer location.

The display (1202) is the same view, but with the display opacity of the skull material reduced. This reduced opacity makes the internal structure (1107) clearly visible, as shown in the Figure. During actual use, the system enables the surgeon to vary this opacity in real time to adjust the image so that both the skull structure and the internal structure are visible in the display in various proportions.

It will be noted that the surface contour lines shown in the display (1201) are produced by the finite size of the rendering layers or voxels. These contour lines may be reduced by smoothing the data, or by reducing the sizes of the voxels or layers.

Figure 13 is a composite of two further displays with the pointer (1104) moved to extend through one of the openings (1103). Display (1302) is the view from the tip of the pointer inside the skull. Display (1301) is a view of the entire structure from outside the skull along the pointer axis; in other words, display (1302) is substantially a magnification of part of display (1301). Display (1301) shows the skull with a portion cut away by a cutting plane through the tip of the pointer, perpendicular to the pointer axis. Both of these displays clearly illustrate the perspective nature of the three-dimensional displays generated by the present invention.

Finally, Figure 14 is a simplified composite of displays generated by the system for an actual human head. Display (1401) is a perspective view of the entire head with a cutaway portion defined by orthogonal cutting planes as shown. The edge of the display in Figure 14 is shown by the border (1400). This display also shows the field of view of an endoscope pointing toward the head along the intersection line of the two cutting planes, with the tip of the endoscope at the apex of the cone. Display (1402) shows the two-dimensional sectional view produced by the vertical cutting plane, and display (1403) shows the corresponding

sectional view produced by the horizontal cutting plane. Furthermore, the images in displays (1402) and (1403) are also transformed (rotated and magnified) and superimposed on the three-dimensional image in display (1401).

Both of these displays indicate also the intersection of the cutting planes with the conical field of view. Display (1404) is the actual image seen by the endoscope. Display (1405) is a virtual perspective view of the endoscope image reconstructed from scan data by volume rendering in accordance with the present invention. Display (1406) is a virtual perspective view of the image from the endoscope viewpoint with a narrower field of view, reconstructed from scan data by surface rendering in accordance with the present invention. This display (1406) would be used with a surgical probe in planning a surgical trajectory. Display (1407) is a magnification of (1406) (i.e. with a narrower field of view) showing the virtual image that would be seen through a microscope. Finally, display (1408) is a segmented three-dimensional perspective view of the entire head from the scan data utilizing surface rendering, and display (1409) is the same view with volume rendering. Figure 14 illustrates the rich variety and versatility of the displays that are possible with the present system. All of these displays are presented to the surgeon in real time, simultaneously, and can be varied on line.

It is apparent from the foregoing description that this invention provides improved means for navigating through the anatomy during actual surgical procedures. The system enables the surgeon to select and adjust the display with the same tool that is being utilized to perform the procedure, without requiring extra manual operations. Since the displays are provided immediately in real time, the imaging does not require any interruption of the procedure. In addition, the virtual images provided by this system are

continuously correlated with the images that are obtained through conventional means.

It will be further appreciated by persons of ordinary skill in the art that the invention is not limited in its application to neurosurgery, or any other kind of surgery or medical diagnostic applications. For example, systems implementing the invention can be implemented for actual nautical or aviation navigation utilizing information from satellites to obtain the "pre-op" scan data. The pointing device can be implemented by the vessel or aircraft itself, and the video display could be replaced by special imaging goggles or helmets.

The foregoing description of the preferred embodiments of the invention has been presented solely for purposes of illustration and description, and is not exhaustive or limited to the precise forms disclosed. Many modifications and variations are possible in light of the above teaching. The spirit and scope of the invention are to be defined by reference to the following claims, along with their full scope of equivalents.

Claims

1. A method for generating an image of a three-dimensional object, said method comprising the steps of:

acquiring volumetric first scan data for the object;

utilizing said first scan data to reconstruct first virtual image data representing structural information in said first scan data;

selecting a viewpoint for displaying an image of said object based on said first virtual image data;

manipulating said first virtual image data to generate a first three-dimensional perspective image of said object from said viewpoint; and

displaying said first three-dimensional perspective image.

2. The method recited in claim 1, wherein the step of utilizing said first scan data to reconstruct first virtual image data representing structural information in said first scan data includes the step of segmenting said first virtual image data to distinguish selected features of said object.

3. The method recited in claim 1, wherein the step of utilizing said first scan data to reconstruct first virtual image data representing structural information in said first scan data includes the step of registration of said first virtual image data in relation to said object to determine the location of features of said object represented in said first virtual image data.

4. The method recited in claim 1, further comprising, following the step of displaying said first three-dimensional perspective image, repeating any desired number of times the steps of:

selecting another viewpoint for displaying an image of

said object based on said first virtual image data;

manipulating said first virtual image data to generate a first three-dimensional perspective image of said object from said other viewpoint; and

displaying said first three-dimensional perspective image.

5. The method recited in claim 1, further comprising the steps of:

acquiring volumetric second scan data for the object;

utilizing said second scan data to reconstruct second virtual image data representing structural information in said second scan data;

determining the viewpoint for displaying an image of said object based on said second virtual image data to coincide with said viewpoint selected for displaying an image of said object based on said virtual image data;

manipulating said second virtual image data to generate a second three-dimensional perspective image of said object from said viewpoint; and

displaying said second three-dimensional perspective image.

6. The method recited in claim 5, further comprising the step of fusing said second three-dimensional perspective image and said first three-dimensional perspective image to display a combined image.

7. The method recited in claim 1, further comprising the steps of:

acquiring second scan data for the object;

utilizing said second scan data to reconstruct second virtual image data representing structural information in said second scan data;

determining the viewpoint for displaying an image of

said object based on said second virtual image data to coincide with said viewpoint selected for displaying an image of said object based on said virtual image data;

manipulating said second virtual image data to generate a second image of said object from said viewpoint; and

displaying said second image.

8. The method recited in claim 7, further comprising the step of fusing said second image and said first three-dimensional perspective image to display a combined image.

9. Apparatus for generating an image of a three-dimensional object, comprising:

a computer having a memory;

display means communicative with said computer;

input means communicative with said computer;

pointer means communicative with said computer, said pointer means being movable by the user; and

position tracking means communicative with said computer and said pointing means, such that said position tracking means detects the position and orientation of said pointer means continually and communicates said position and orientation to said computer;

wherein said computer memory contains volumetric first scan data for the object, and further contains a program which causes said computer to perform the steps of:

utilizing said first scan data to reconstruct first virtual image data representing structural information in said first scan data;

determining a viewpoint for displaying an image of said object based on said first virtual image data to be the position and orientation of said pointer means detected by said position tracking means;

manipulating said first virtual image data to generate a first three-dimensional perspective image of said object

from said viewpoint; and

displaying said first three-dimensional perspective image.

10. Apparatus as recited in claim 9, wherein the step of utilizing said first scan data to reconstruct first virtual image data representing structural information in said first scan data includes the step of segmenting said first virtual image data to distinguish selected features of said object.

11. Apparatus as recited in claim 9, wherein the step of utilizing said first scan data to reconstruct first virtual image data representing structural information in said first scan data includes the step of registration of said first virtual image data in relation to said object to determine the location of features of said object represented in said first virtual image data.

12. Apparatus as recited in claim 9, wherein said program causes said computer, following the step of displaying said first three-dimensional perspective image, to perform and repeat any desired number of times the further steps of:

selecting another viewpoint for displaying an image of said object based on said first virtual image data;

manipulating said first virtual image data to generate a first three-dimensional perspective image of said object from said other viewpoint; and

displaying said first three-dimensional perspective image.

13. Apparatus as recited in claim 9, wherein said program causes said program performs the further steps of:

acquiring volumetric second scan data for the object;

utilizing said second scan data to reconstruct second virtual image data representing structural information in said second scan data;

determining the viewpoint for displaying an image of said object based on said second virtual image data to coincide with said viewpoint selected for displaying an image of said object based on said virtual image data;

manipulating said second virtual image data to generate a second three-dimensional perspective image of said object from said viewpoint; and

displaying said second three-dimensional perspective image.

14. Apparatus as recited in claim 13, wherein said program performs the further step of fusing said second three-dimensional perspective image and said first three-dimensional perspective image to display a combined image.

15. Apparatus as recited in claim 9, wherein said program performs the further steps of:

acquiring second scan data for the object;

utilizing said second scan data to reconstruct second virtual image data representing structural information in said second scan data;

determining the viewpoint for displaying an image of said object based on said second virtual image data to coincide with said viewpoint selected for displaying an image of said object based on said virtual image data;

manipulating said second virtual image data to generate a second image of said object from said viewpoint; and

displaying said second image.

16. Apparatus as recited in claim 15, wherein said program performs the further step of fusing said second image and said first three-dimensional perspective image to

display a combined image.

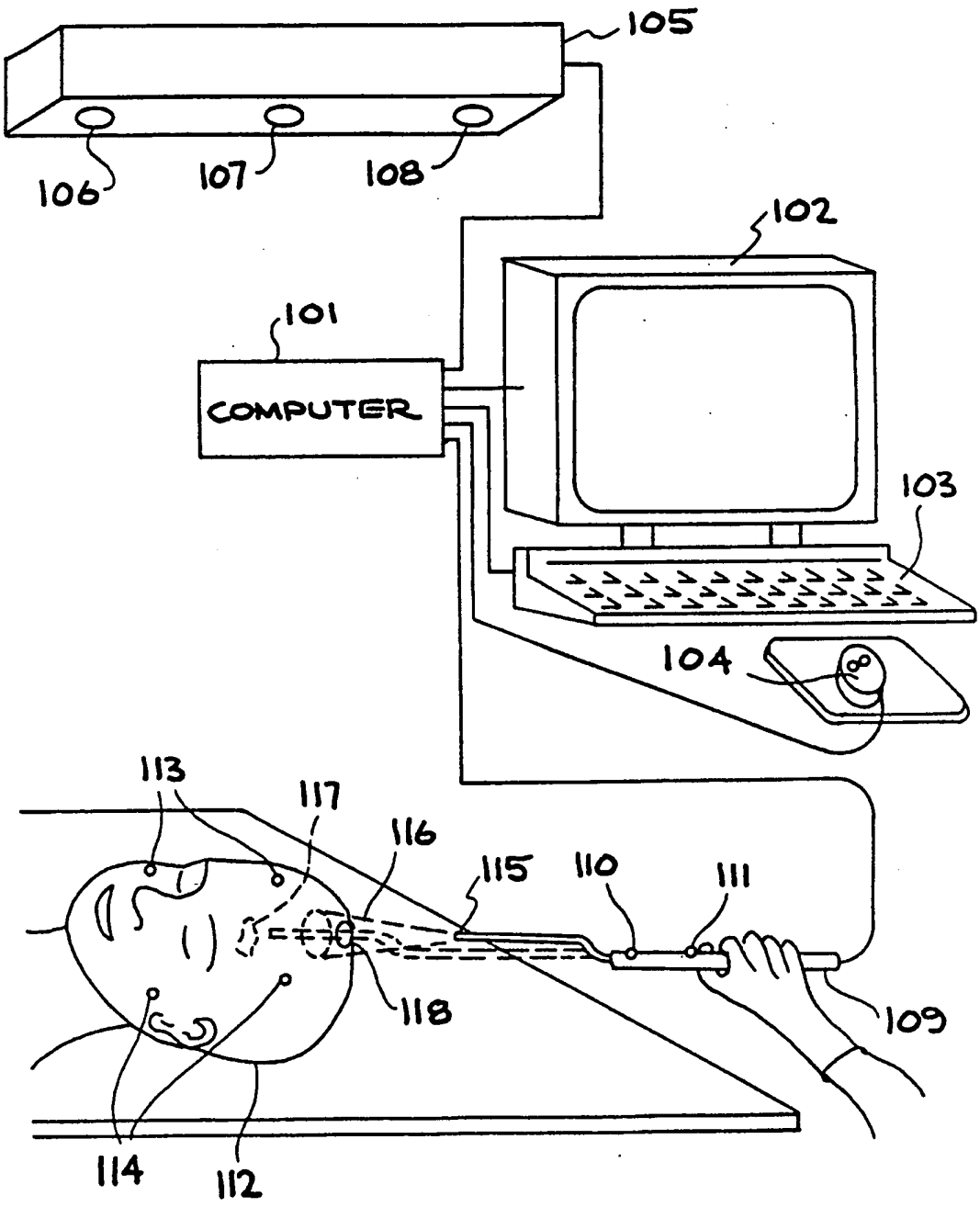
105
106
107
108
102
101
COMPUTER
103
104
113
117
116
115
110
111
118
109
114
112

FIG. 1

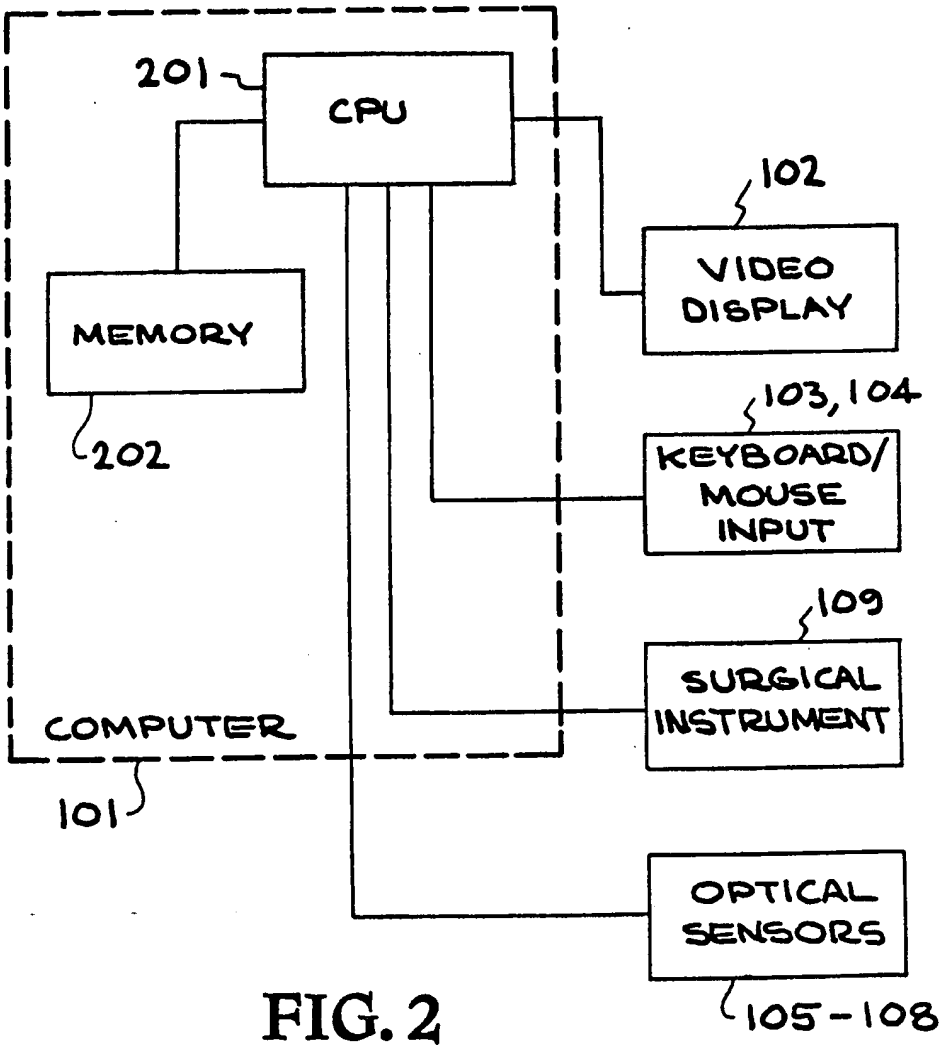
201
CPU
102
VIDEO DISPLAY
MEMORY
202
103, 104
KEYBOARD/ MOUSE INPUT
109
SURGICAL INSTRUMENT
COMPUTER
101
OPTICAL SENSORS
105-108

FIG. 2

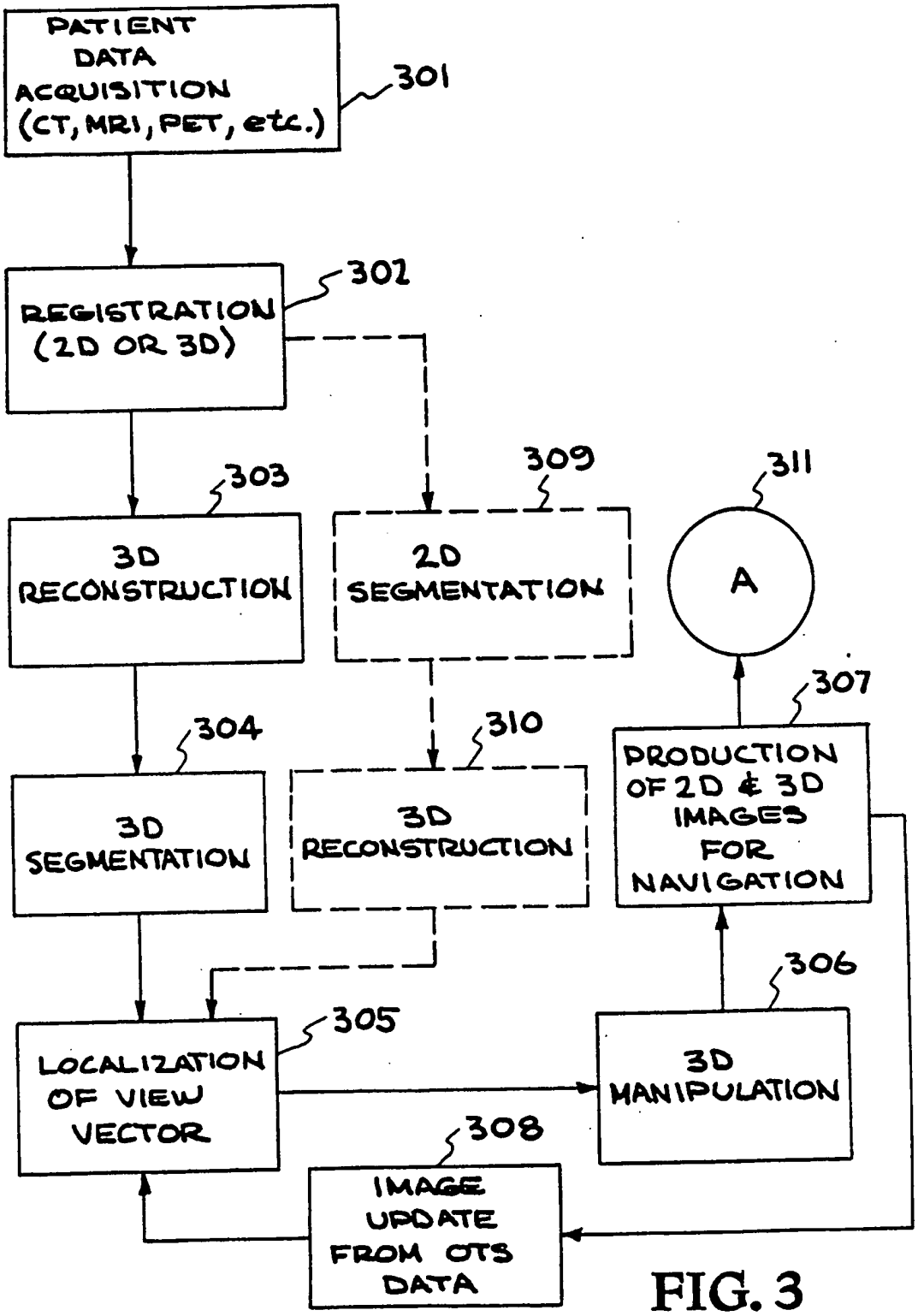
PATIENT DATA ACQUISITION (CT, MRI, PET, etc.)
301
REGISTRATION (2D OR 3D)
302
3D RECONSTRUCTION
303
2D SEGMENTATION
309
A
311
3D SEGMENTATION
304
3D RECONSTRUCTION
310
PRODUCTION OF 2D & 3D IMAGES FOR NAVIGATION
307
LOCALIZATION OF VIEW VECTOR
305
3D MANIPULATION
306
IMAGE UPDATE FROM OTS DATA
308

FIG. 3

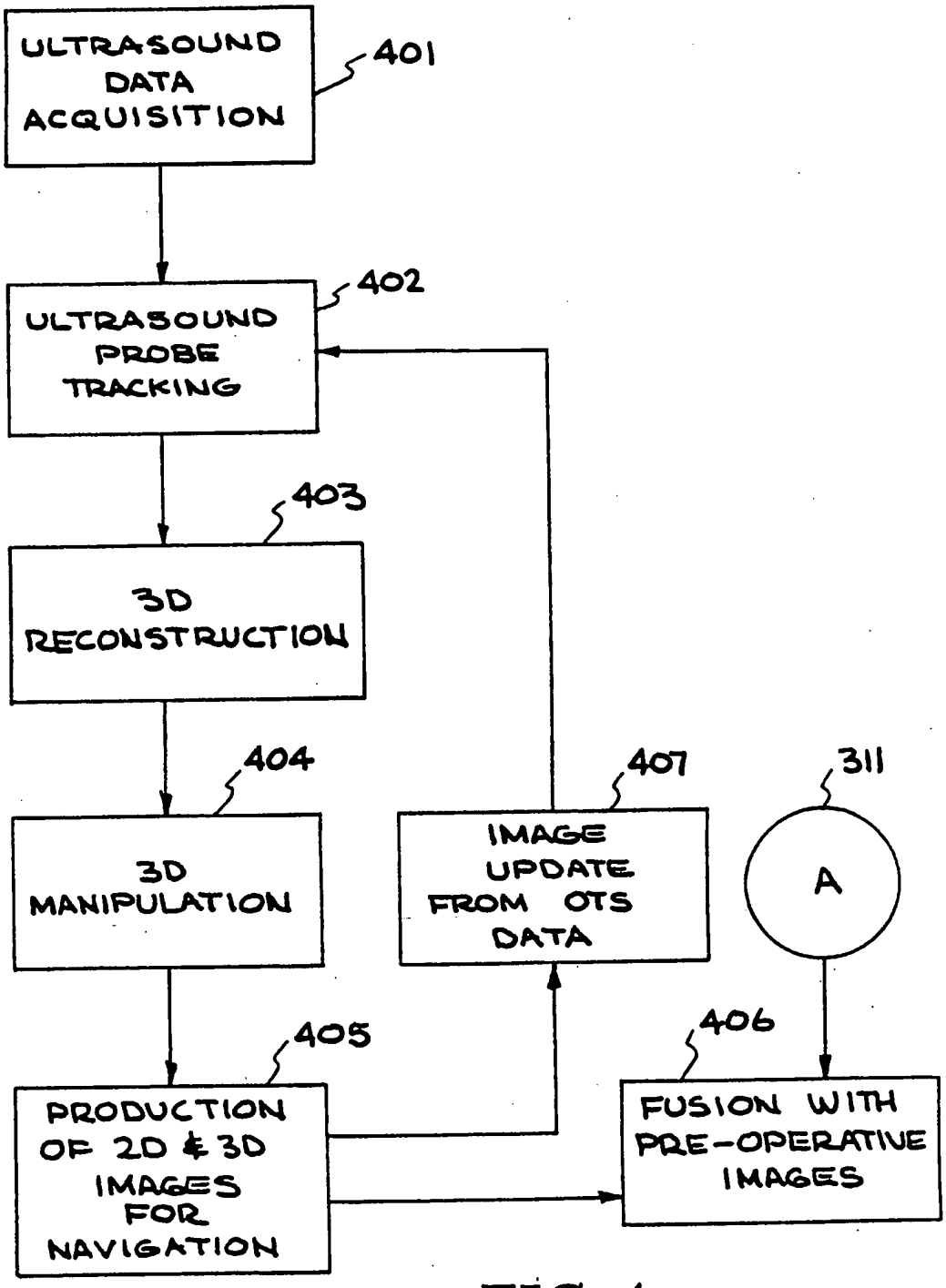
ULTRASOUND DATA ACQUISITION
401
ULTRASOUND PROBE TRACKING
402
3D RECONSTRUCTION
403
3D MANIPULATION
404
IMAGE UPDATE FROM OTS DATA
407
A
311
PRODUCTION OF 2D & 3D IMAGES FOR NAVIGATION
405
FUSION WITH PRE-OPERATIVE IMAGES
406

FIG. 4

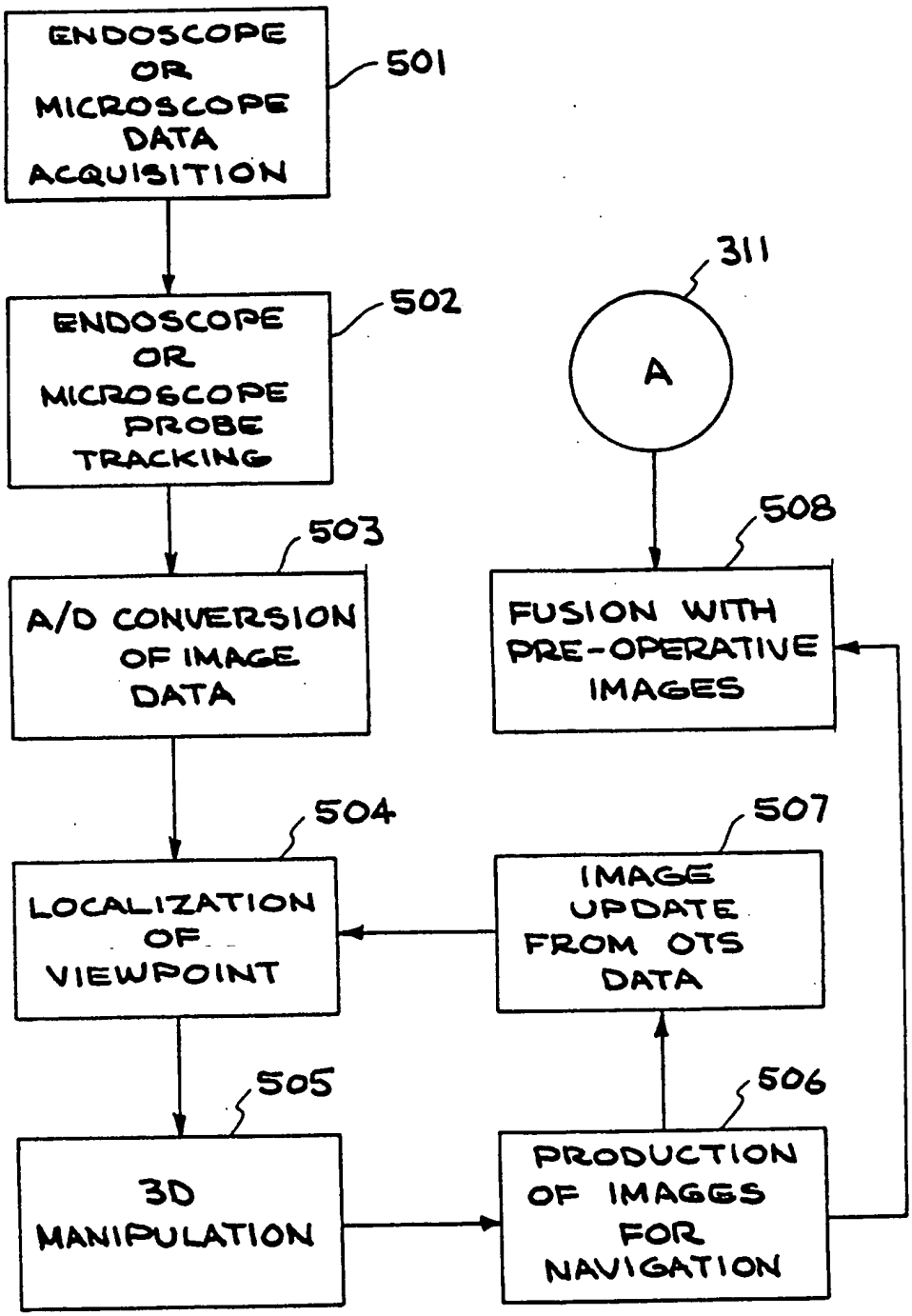
ENDOSCOPE OR MICROSCOPE DATA ACQUISITION
501
ENDOSCOPE OR MICROSCOPE PROBE TRACKING
502
311
A
A/D CONVERSION OF IMAGE DATA
503
508
FUSION WITH PRE-OPERATIVE IMAGES
504
507
LOCALIZATION OF VIEWPOINT
IMAGE UPDATE FROM OTS DATA
505
506
3D MANIPULATION
PRODUCTION OF IMAGES FOR NAVIGATION

FIG.5

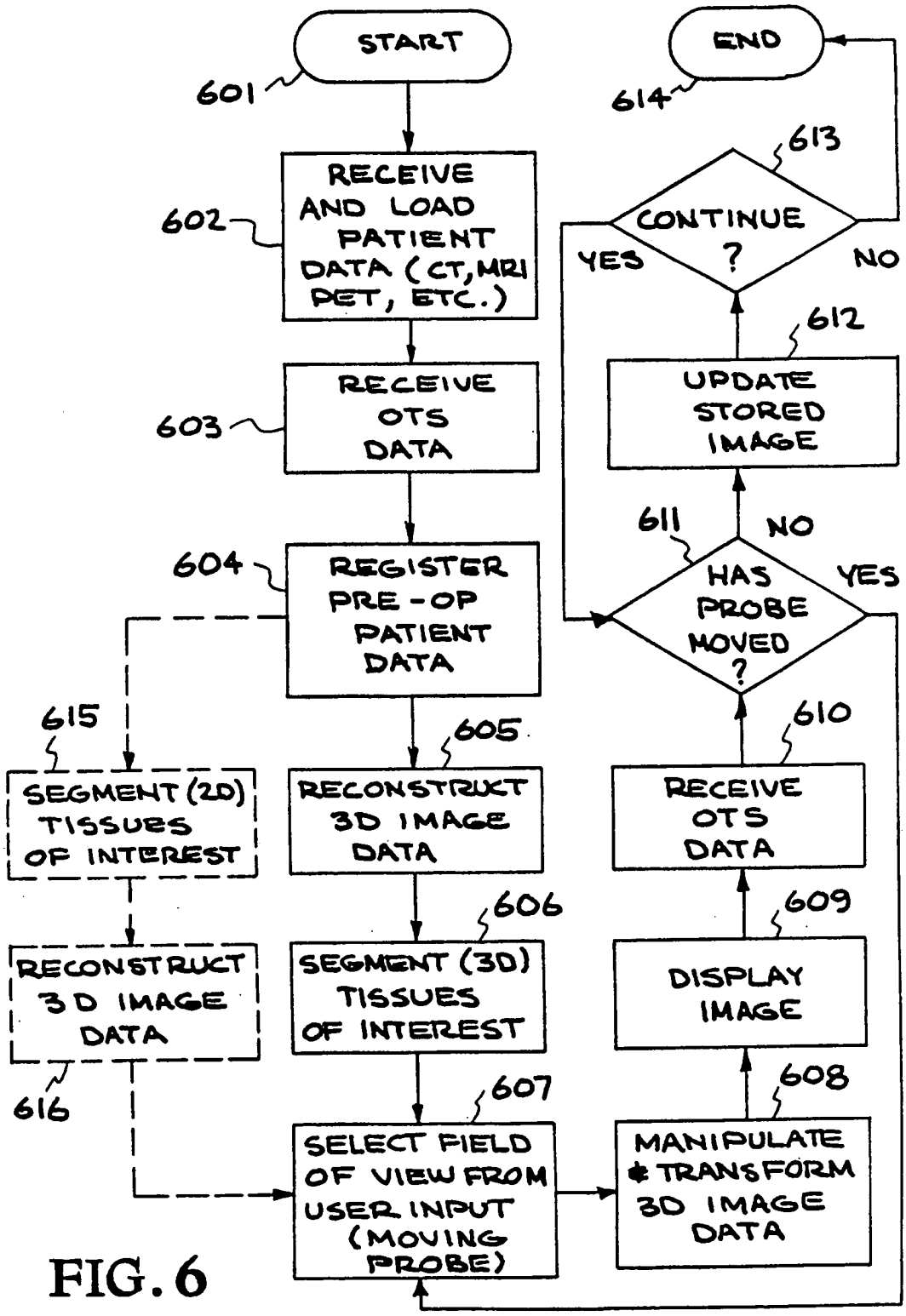
START
601
RECEIVE AND LOAD PATIENT DATA (CT, MRI PET, ETC.)
602
RECEIVE OTS DATA
603
REGISTER PRE-OP PATIENT DATA
604
SEGMENT (2D) TISSUES OF INTEREST
615
RECONSTRUCT 3D IMAGE DATA
616
RECONSTRUCT 3D IMAGE DATA
605
SEGMENT (3D) TISSUES OF INTEREST
606
SELECT FIELD OF VIEW FROM USER INPUT (MOVING PROBE)
607
MANIPULATE & TRANSFORM 3D IMAGE DATA
608
DISPLAY IMAGE
609
RECEIVE OTS DATA
610
HAS PROBE MOVED ?
611
YES
NO
UPDATE STORED IMAGE
612
CONTINUE ?
613
YES
NO
END
614

FIG. 6

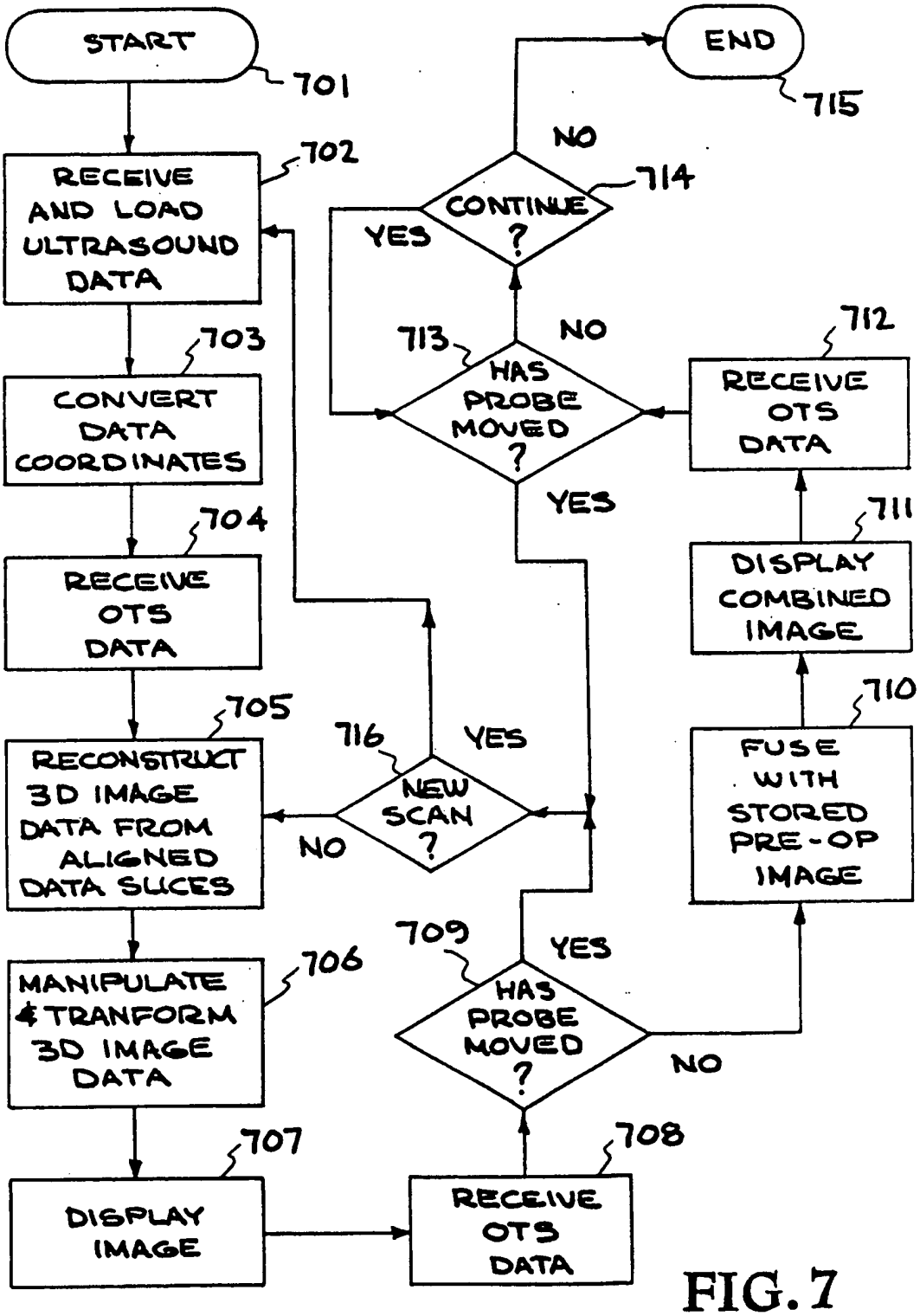
START
701
RECEIVE AND LOAD ULTRASOUND DATA
702
CONVERT DATA COORDINATES
703
RECEIVE OTS DATA
704
RECONSTRUCT 3D IMAGE DATA FROM ALIGNED DATA SLICES
705
MANIPULATE & TRANFORM 3D IMAGE DATA
706
DISPLAY IMAGE
707
RECEIVE OTS DATA
708
HAS PROBE MOVED ?
709
YES
NO
FUSE WITH STORED PRE-OP IMAGE
710
DISPLAY COMBINED IMAGE
711
RECEIVE OTS DATA
712
HAS PROBE MOVED ?
713
YES
NO
CONTINUE ?
714
YES
NO
END
715
NEW SCAN ?
716
YES
NO

FIG. 7

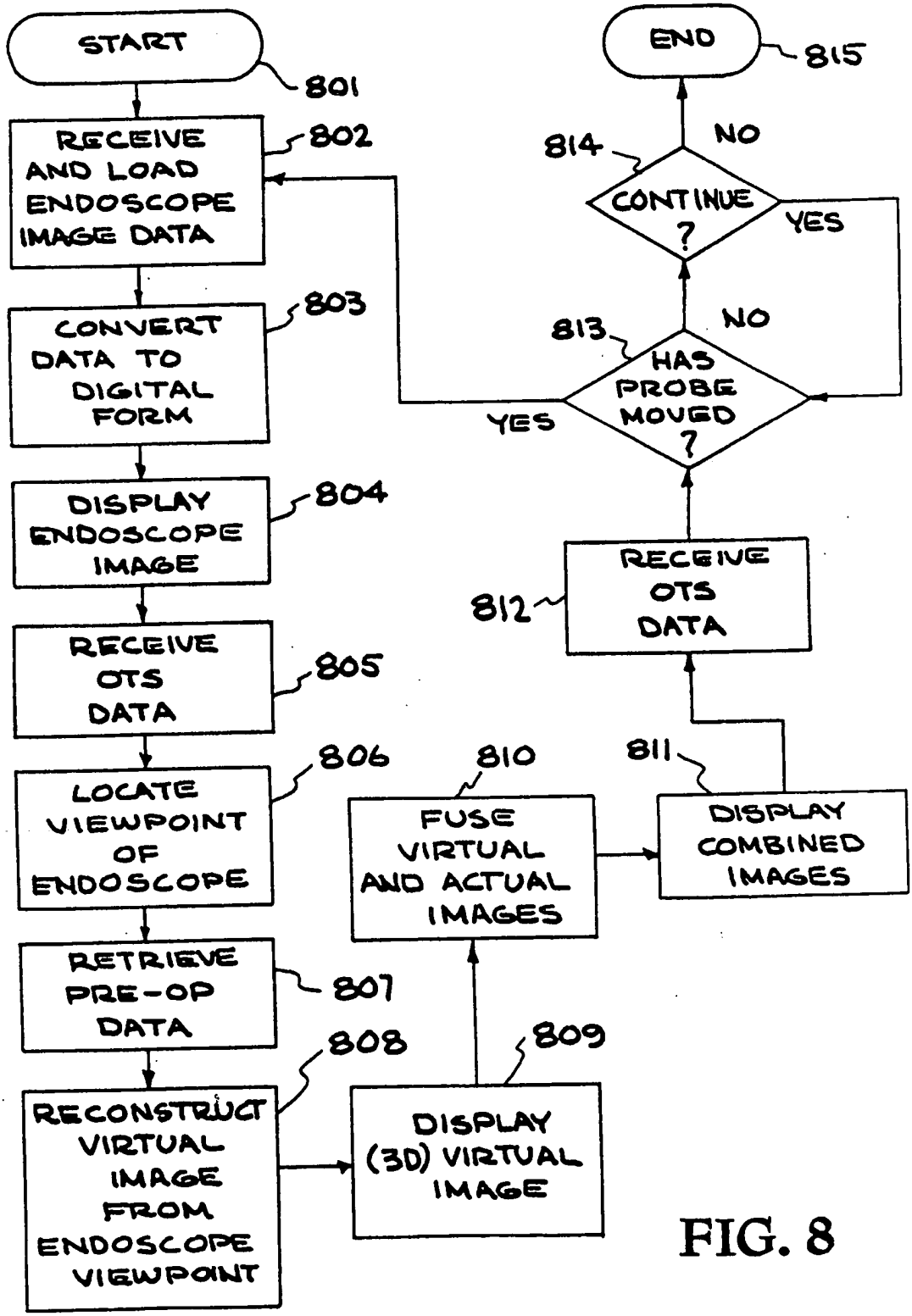
START
801
RECEIVE AND LOAD ENDOSCOPE IMAGE DATA
802
CONVERT DATA TO DIGITAL FORM
803
DISPLAY ENDOSCOPE IMAGE
804
RECEIVE OTS DATA
805
LOCATE VIEWPOINT OF ENDOSCOPE
806
RETRIEVE PRE-OP DATA
807
RECONSTRUCT VIRTUAL IMAGE FROM ENDOSCOPE VIEWPOINT
808
DISPLAY (3D) VIRTUAL IMAGE
809
FUSE VIRTUAL AND ACTUAL IMAGES
810
DISPLAY COMBINED IMAGES
811
RECEIVE OTS DATA
812
HAS PROBE MOVED ?
813
YES
NO
CONTINUE ?
814
YES
NO
END
815

FIG. 8

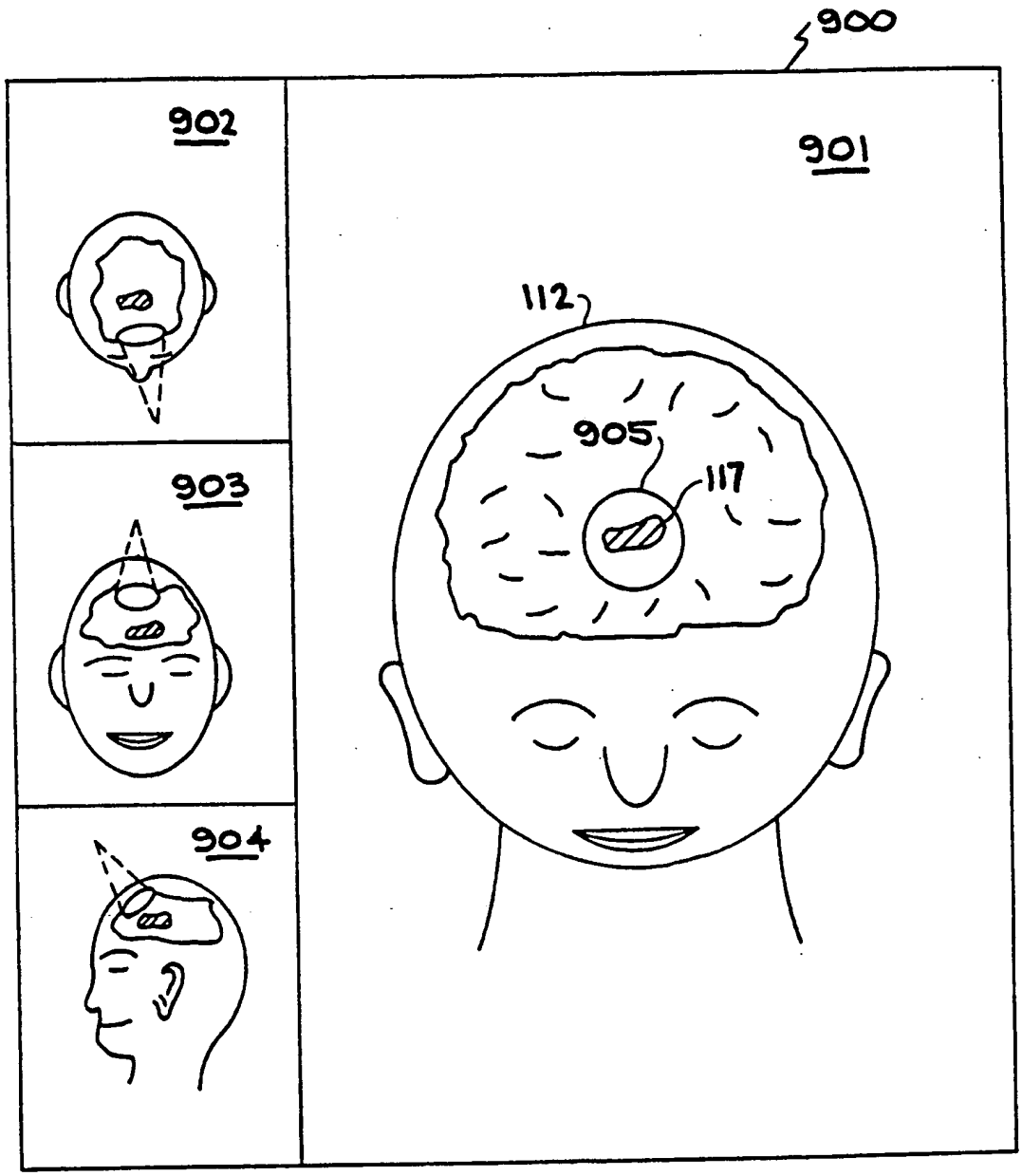

FIG. 9

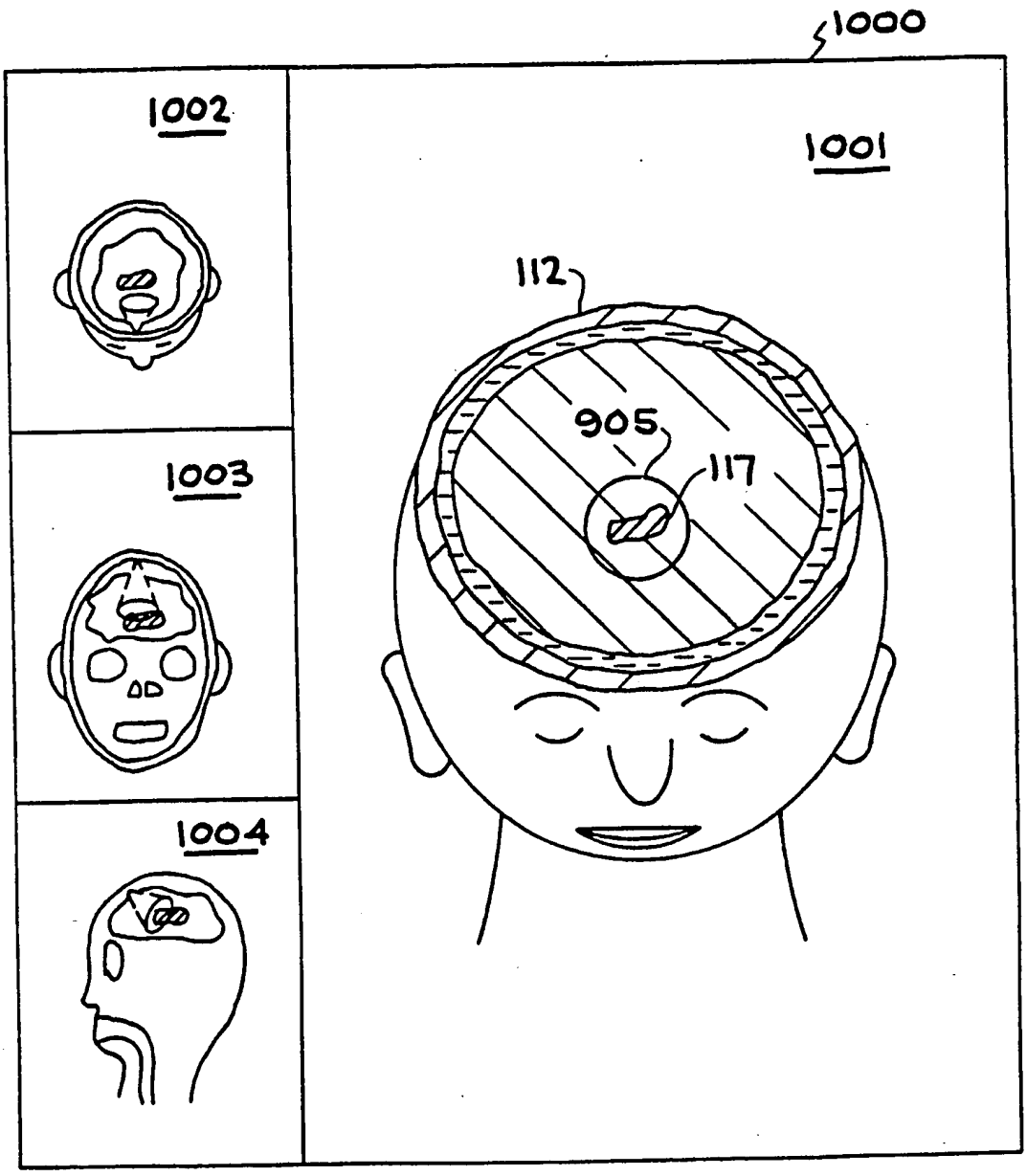

FIG. 10

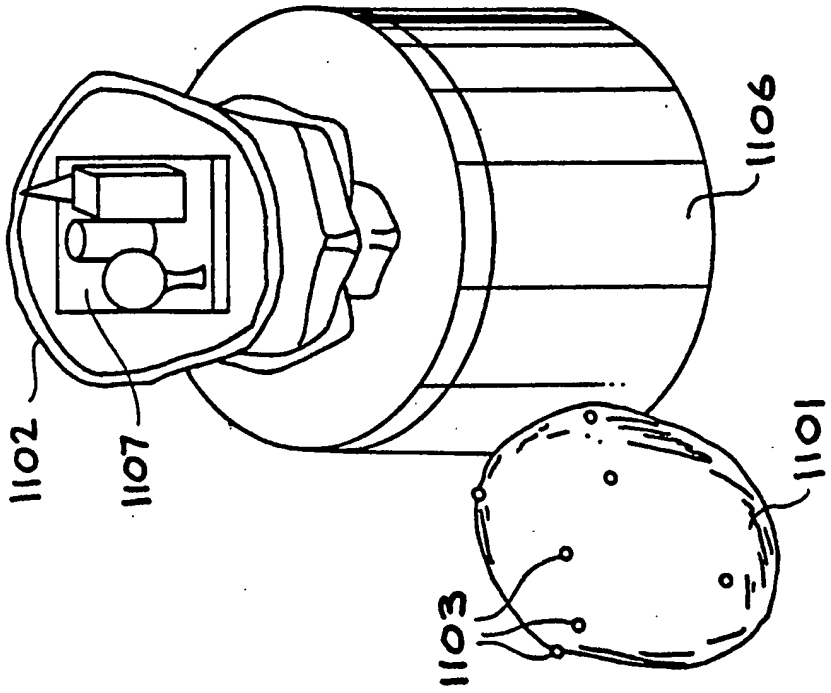

FIG. 11B

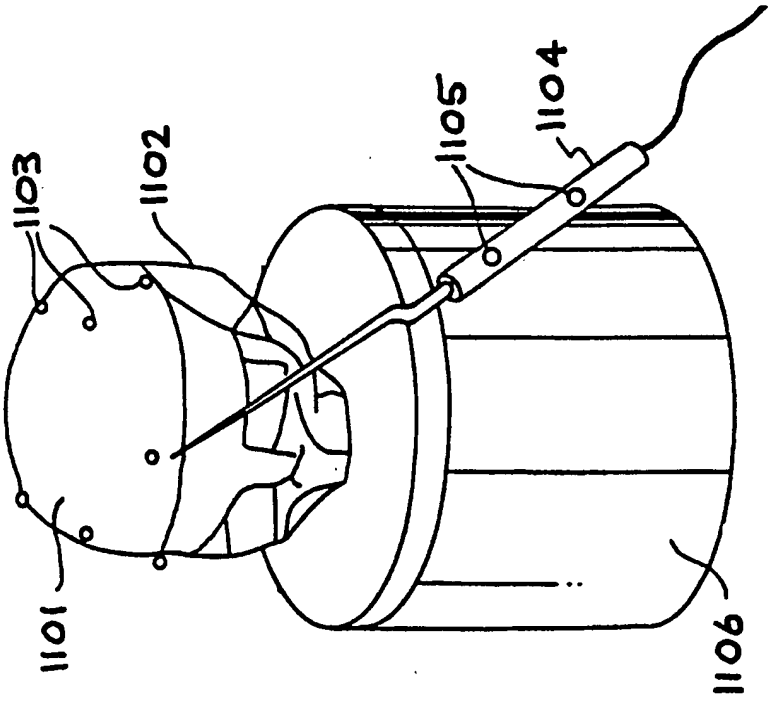

FIG. 11A

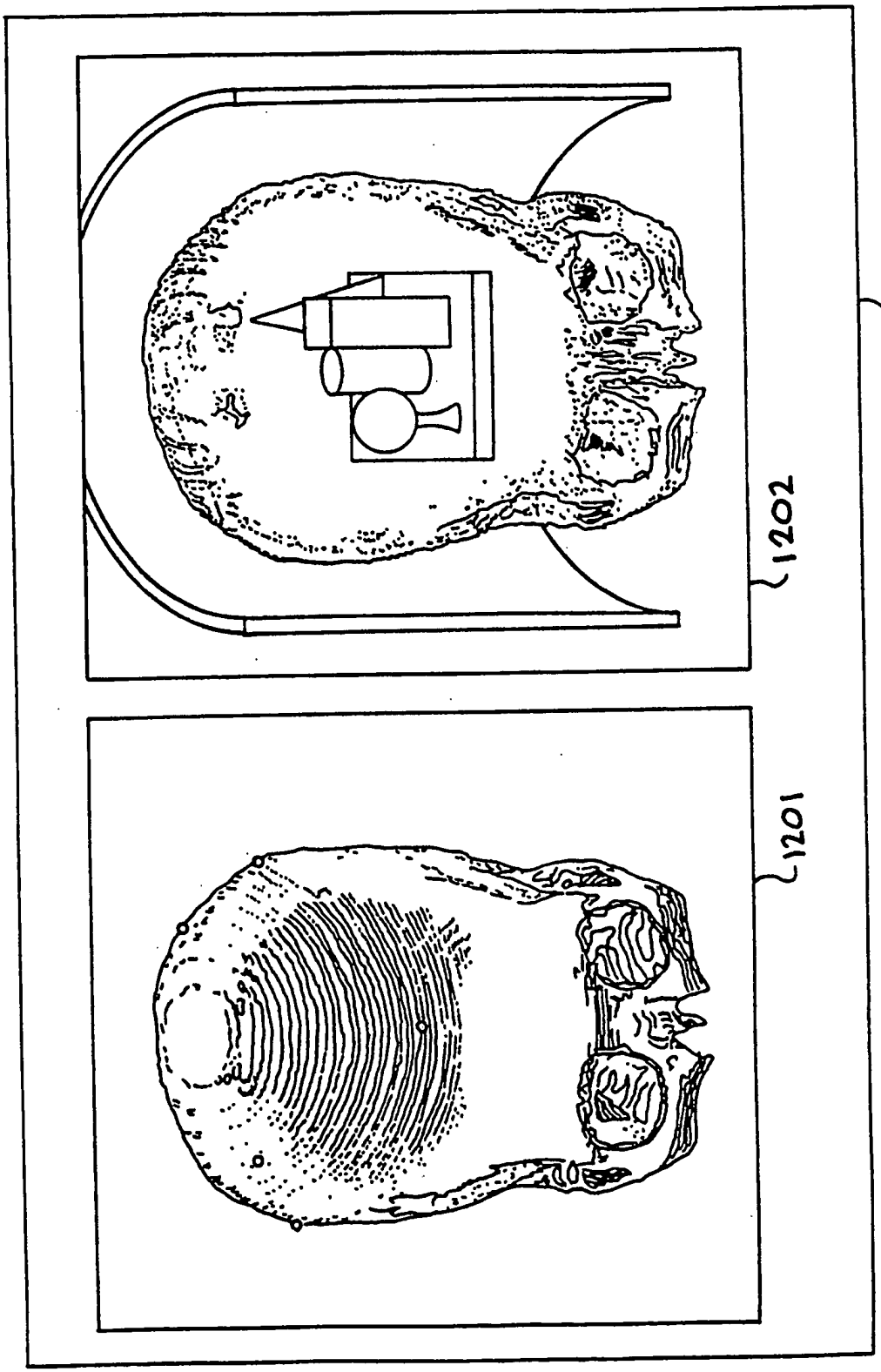

FIG. 12

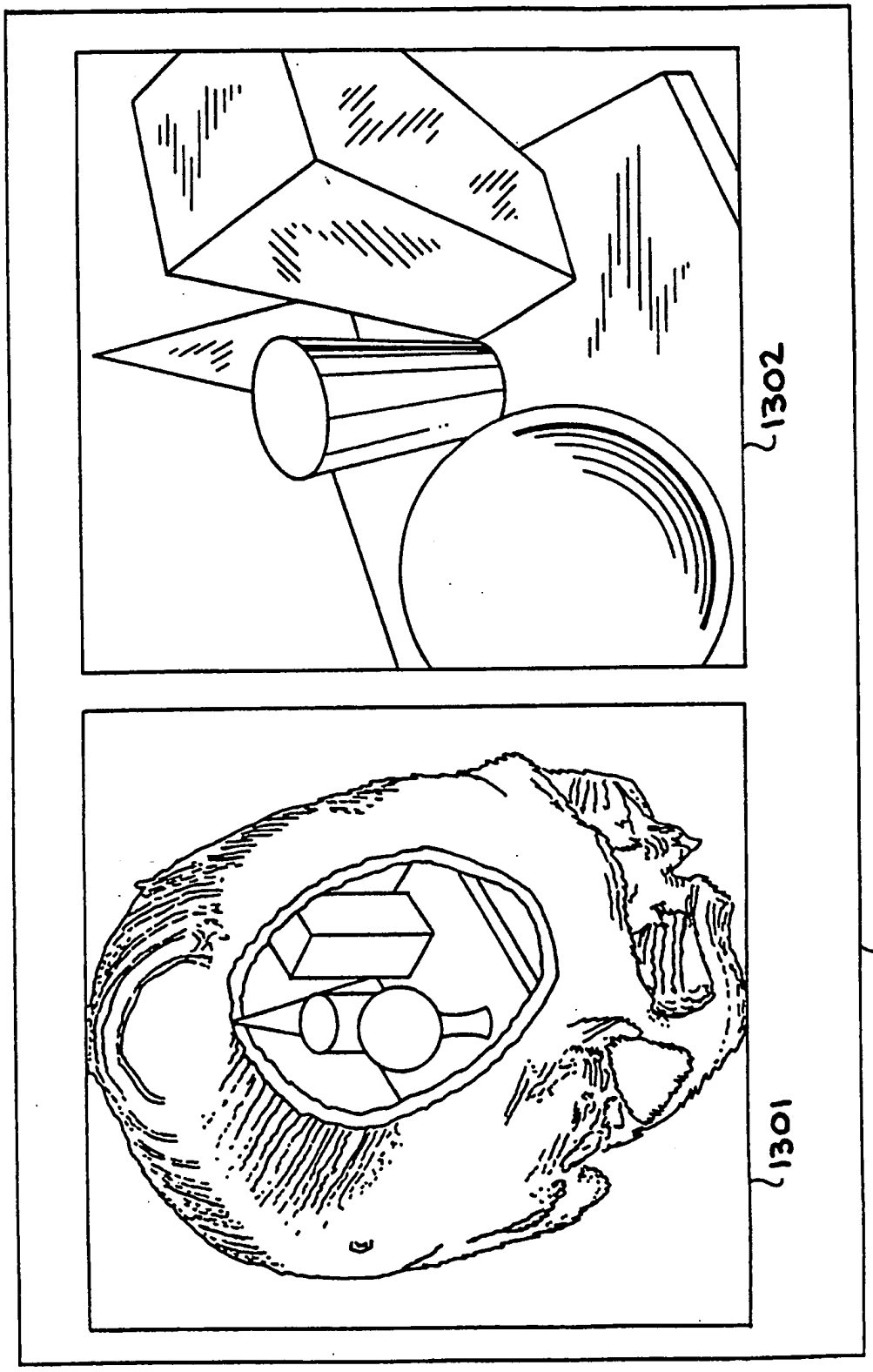

FIG. 13

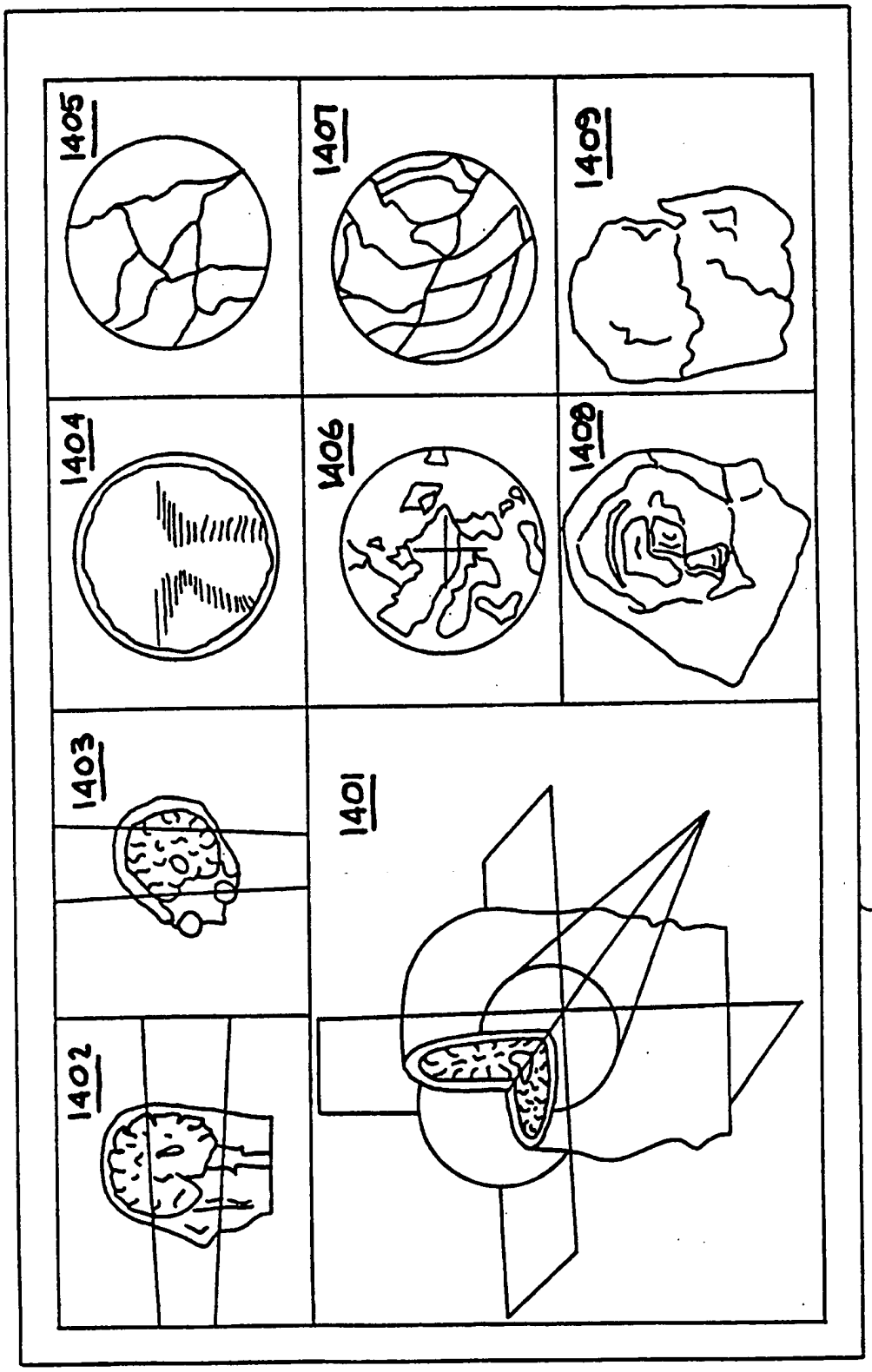

FIG. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/13391

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :A61B 5/00
US CL :600/425-427, 429; 606/130

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 600/414, 417, 425-427, 429; 606/130

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,622,170 A (SCHULZ) 22 April 1997 (22/04/97), entire document.	1-4, 9-12
X, E	US 5,800,352 A (FERRE et al.) 01 September 1998 (01/09/98), entire document.	1-16

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

*	Special categories of cited documents:	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E"	earlier document published on or after the international filing date	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"&"	document member of the same patent family
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed		

Date of the actual completion of the international search
17 SEPTEMBER 1998

Date of mailing of the international search report
19 OCT 1998

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